

RF Wave Experiments of Astroparticles of Taiwan

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LeCosPA, NTU

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Outline:

- Cosmic Rays & Neutrino
- Experiments - ANITA
- Experiments - ARA
- Experiments - TAROGE
- Results and Future Plans



Team Members



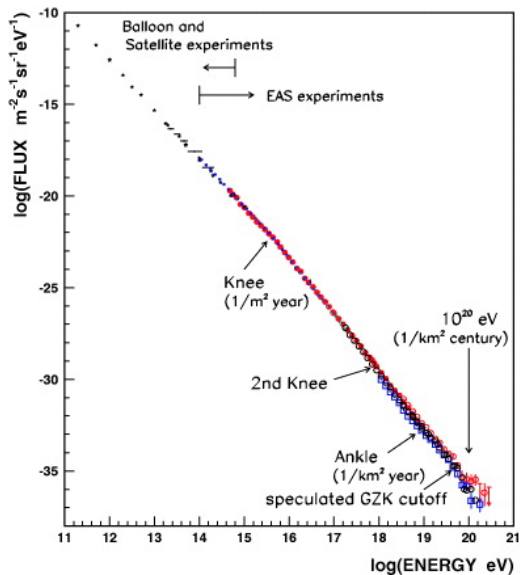
Figure : Experiment group of LeCosPA center.

Unsolved Problems of UHECR & UHECN

- What accelerates the cosmic particles?
- Where are the sources?
- Neutrino hierarchy?
- Beyond standard oscillation?
- Neutrino cross section at UHE ?
- How many generations of neutrino?
- Absolute mass of the neutrinos?



From Cosmic Rays to Neutrino



From Cosmic Rays to Neutrino

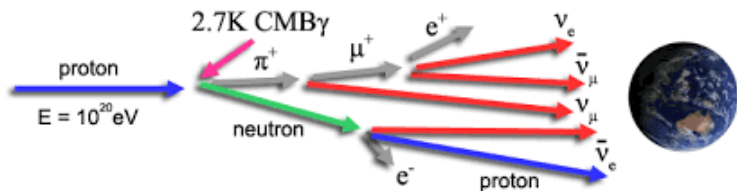


Figure : Neutrino flavor ratio is depend on its energy.



Neutrino Sources and its Propagation

Neutrino Flavor Ratio at Source

$\nu_e:\nu_\mu:\nu_\tau=1:2:0$ (Pion source)

$\nu_e:\nu_\mu:\nu_\tau=0:1:0$ (Muon-damped source)

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

At Earth: Standard Oscillation

1:1:1 (pion source)

1:2:2 (Muon-damped source)

ν Decay Scenario

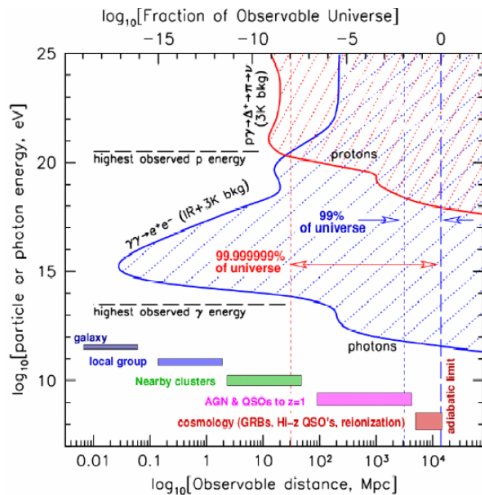
6:1:1 (normal mass hierarchy)

0:1:1 (inverted mass hierarchy)

Figure : Flavor analysis a sharp probe to test ν source, oscillation, decay, and mass hierarchy.



Astrophysics Potentials The Ideal UHE Messenger



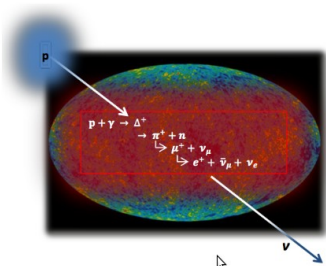
- Photons lost above 100 TeV (pair production on CMB & IR)
- Protons and Nuclei suffer curvature induced by B fields
- But: we know there are sources up to 10^{20} eV!!

UHE Neutrino Detectors Study:

- Highest energy observation of extragalactic sources
- Very distant sources
- Deep into opaque sources

from A. G. Vieregg

UHE Neutrino & GZK Effect

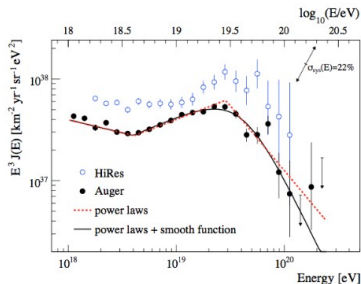


Auger and HiRes measurements of UHE cosmic rays consistent with GZK cut-off

Guaranteed GZK neutrino flux, but how large?

At energies above $\sim 10^{19.5}$ eV cosmic rays will interact with CMB photons producing neutrinos

Process is known as the GZK effect



The Pierre Auger Collaboration (2010): Phys. Lett. B 685 (4-5): 239-246. HiRes Collaboration, Astropart. Phys. 32 (2009) 53.

copy from Jonathan's slides

AAU



GZK Radius

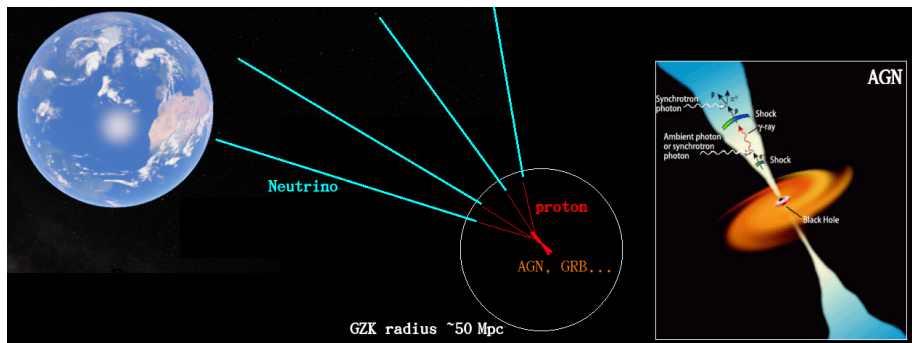


Figure : The UHE neutrinos can point back to the original UHE source without bending of B field.



Short Summary : The UHE Neutrinos

- Trace particle UHECR hyper-accelerators to very early epochs
Even at $z \sim 10$ or more, GZK neutrino energies peak at 10-100 PeV they all point back directly to the UHECR sources
- Their flux is constrained by UHECR sources, once determined
- Neutrino Flavor physics
we can encode source information by flavor ratio, even new physics (neutrino decay?, generations?)



The ANtarctic Impulsive Transient Antenna (ANITA)



The ANITAs

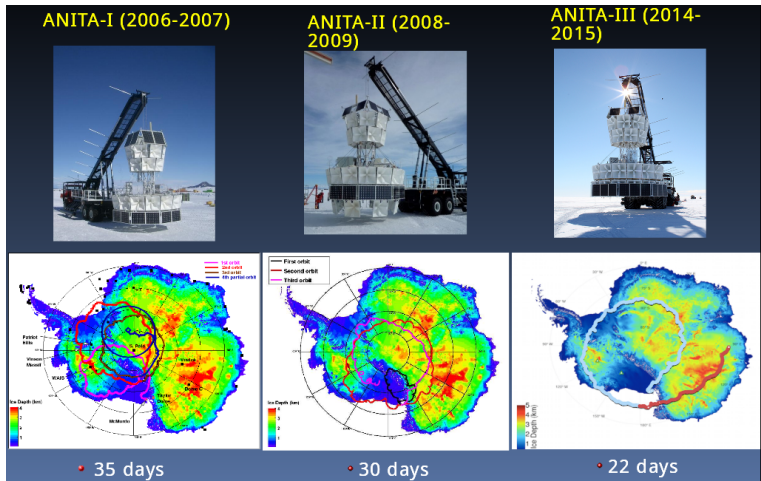


Figure : Three ANITAs were launched until 2015.

The ANtarctic Impulsive Transient Antenna (ANITA-III)

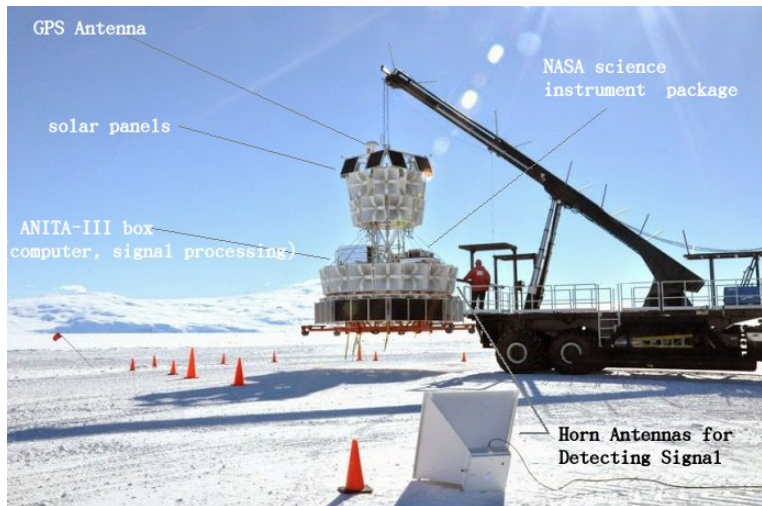


Figure : ANITA-III instrument, 2014-1015.

The ANITA Concept

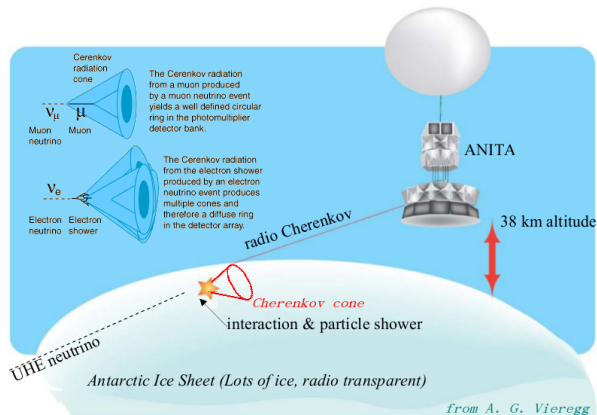
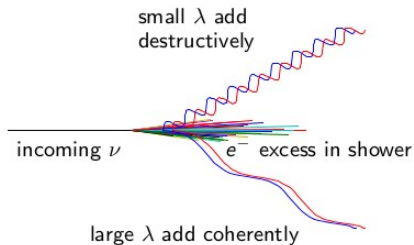


Figure : Cherenkov radiation is electromagnetic radiation emitted when a charged particle passes through a dielectric medium at a speed greater than the velocity of light in that medium.

Coherent Radio Emission (Askaryan Effect)

- Askaryan effect: Neutrinos with energy above ~ 30 PeV most efficiently detected with radio
- Delta-ray production, Compton scattering and positron annihilation give charge excess
- Compact bunch moves together
- Long wavelengths add coherently

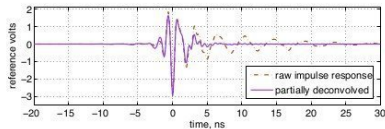


The South Pole has the perfect combination of ice volume, ice RF-transparency, and existing science infrastructure for this experiment.

Askaryan Radiation Experiment in SLAC



Askaryan effect in
sand(2000)
rock salt(2003)
and ice(2006)



PRL 99, 171101 (2007)

see also:

PRE 62, 8590 (2000),

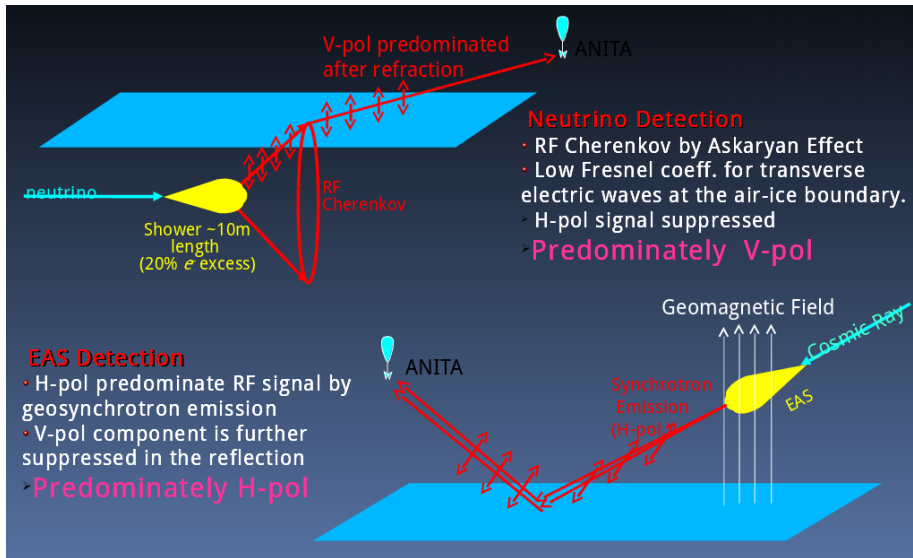
PRL 86, 2802 (2001),

PRD 72, 023002 (2005)

PRD 74, 043002 (2006)

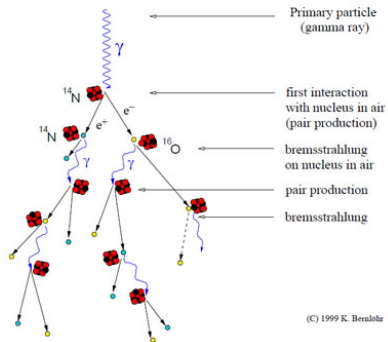
copy from Ryan's slides

Signal Type (neutrino VS. EAS)

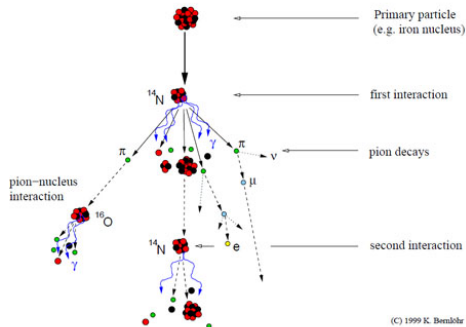


EM Shower & Hadronic shower

Development of gamma-ray air showers



Development of cosmic-ray air showers



Setup of T-510 (Geo-Synchrotron Radiation)

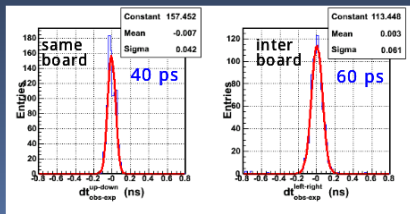
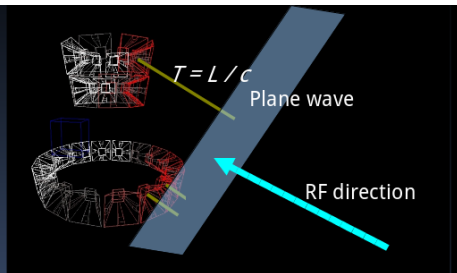


Figure : Electron beam creates secondary cascades in a 4 m long high-density polyethylene (HDPE) target placed in a magnetic field (up to 1000G).

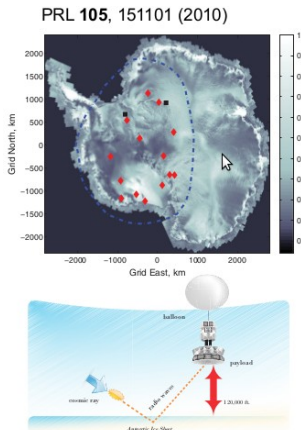
Event Reconstruction

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- Powerful background rejection
 - incoherent thermal events (99% of data set)
 - anthropogenic RF events from existing bases
 - air shower RF events.
- Neutrino reconstruction
 - neutrino direction information
 - provides R and refraction angle for energy measurement.
- Angular reconstruction using timing.
- time resolution; 40-60 ps (time difference between channels)
- Achieved angular resolution; 0.2° (zenith) and 0.8° (azimuth.)

from jiwoo Nam



Results of ANITA I & II (cosmic rays)



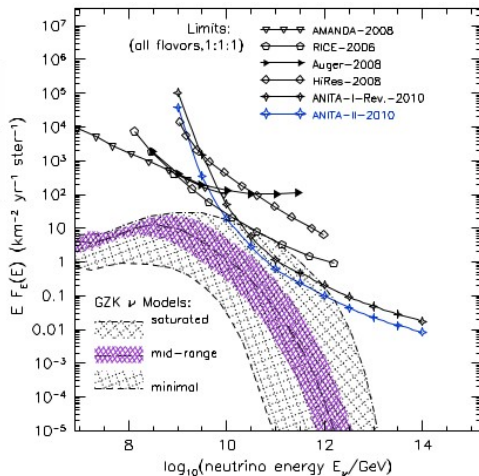
- A combination of $\mathbf{v \times B}$ and Fresnel coefficients result in air shower emission being horizontally polarised at the payload
- ANITA-I detected 16 isolated H-pol candidate UHECR events
- ANITA-II did not trigger on the H-pol channels
–Doh!!
- Still detected 5 UHECR candidate events

Results of ANITA I & II (Neutrino)

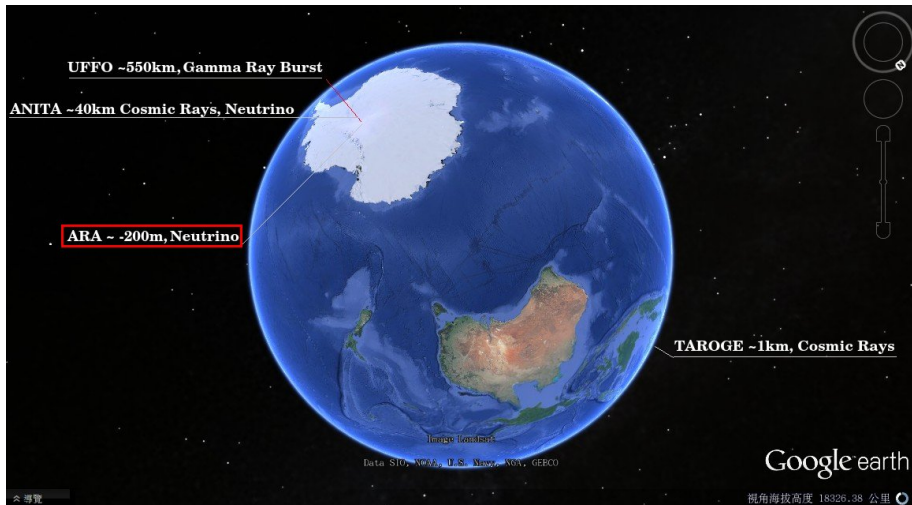
• ANITA-II Results

Isolated v-pol events	1
Expected background events	0.97 ± 0.42

- Combine with efficiency to extract world's best limit on UHE neutrino flux above 10^{19} eV



ARA at -200m



ARA at -200m

The Askaryan Radio Array (ARA) Detecting Neutrinos in Antarctica



ARA-37 Concept

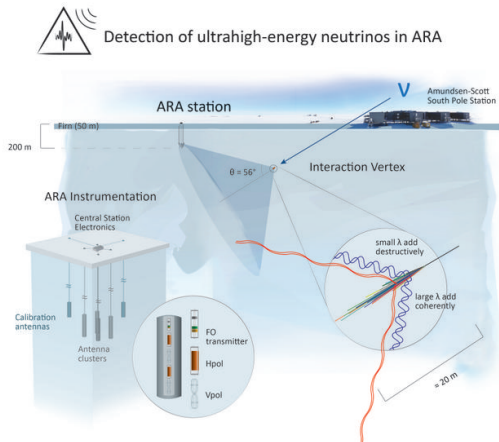


Figure: ARA 37 Layout, 37 Stations 200m below the surface $\sim 200\text{km}^2$ coverage

ARA-37 Concept

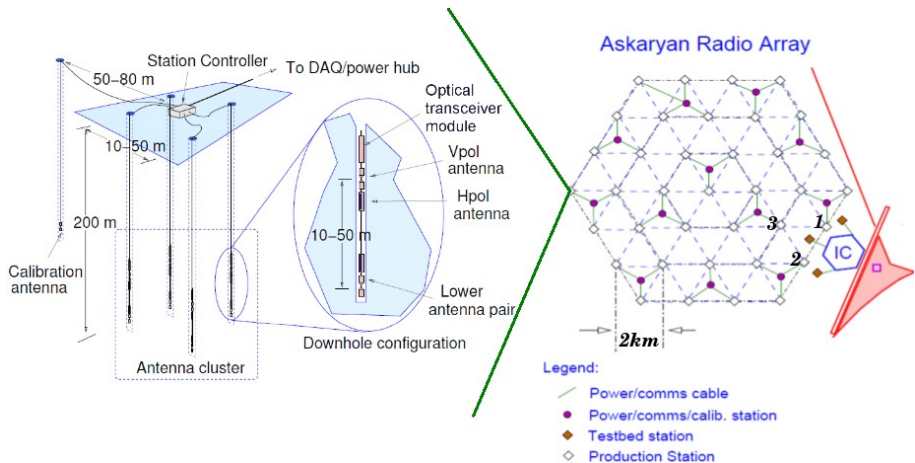
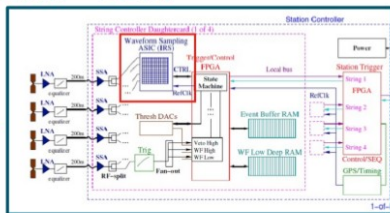
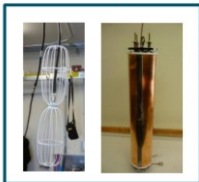


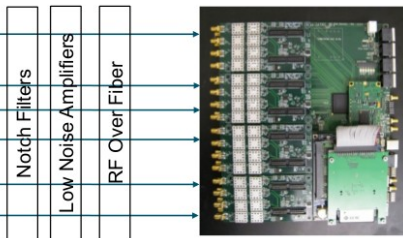
Figure: ARA 37 Layout, 37 Stations 200m below the surface $\sim 200\text{km}^2$ coverage

DAQ System and Antenna Cluster

ARA Sub-Station – DAQ



- 150-850 MHz bandwidth
- 3.2 GSa/s sampling (4x Nyquist)
- Low power consumption
- Autonomous data taking

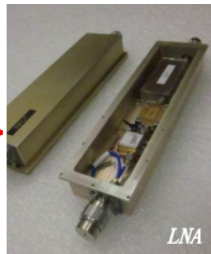


Data Acquisition
Electronics and Computer



Figure : Each station has 4 string with 16 channels

DAQ System and Antenna Cluster



Build & Test in Taiwan

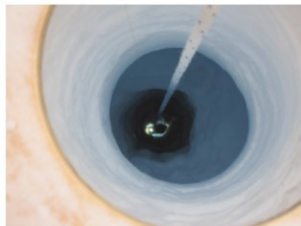


Figure : Building ARA2 & ARA3 last year



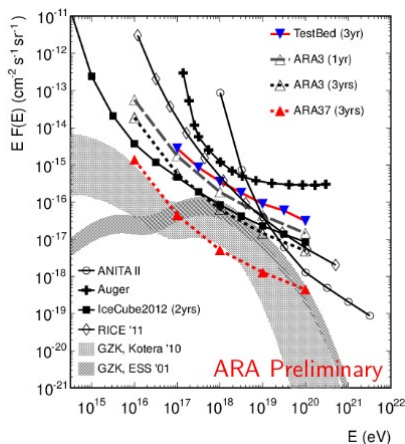
Drilling and Deployment

- Hot water drill creates 6" wide holes
- Holes are pumped dry
- Approaching $\sim 8 \text{ hr} \times \sim 1$ drill crew per 200 m hole
- Instrumentation deployed from greenhouse sled

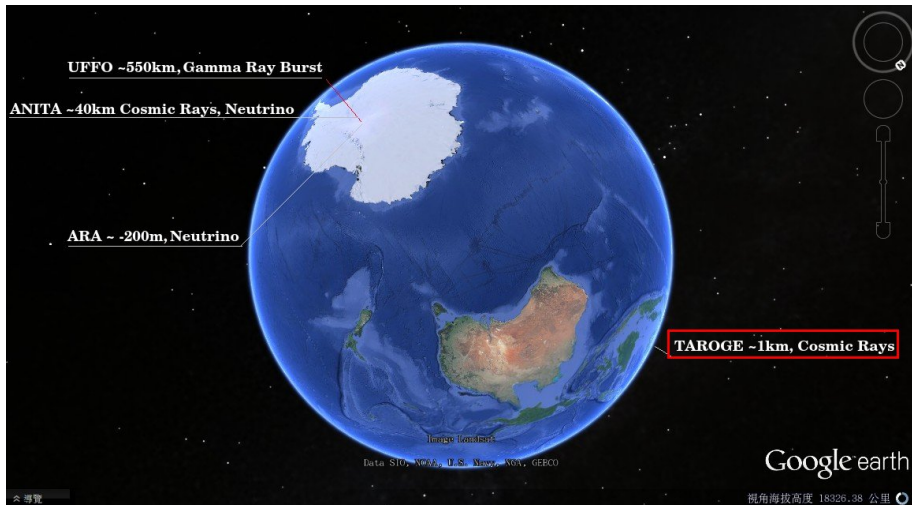


Simulation & Expected Sensitivity

- In-house tool called AraSim
- Simulates
 - neutrino interaction
 - radio emission
 - radio propagation
 - instrument response
 - thermal, instrument noise
 - hardware trigger
 - digitized waveforms
- Has been used to calculate trigger-level neutrino sensitivity



Outline: The Distribution of Experiments



Taiwan Astroparticle Radio wave Observatory for Geo-synchrotron Emission(TAROG)

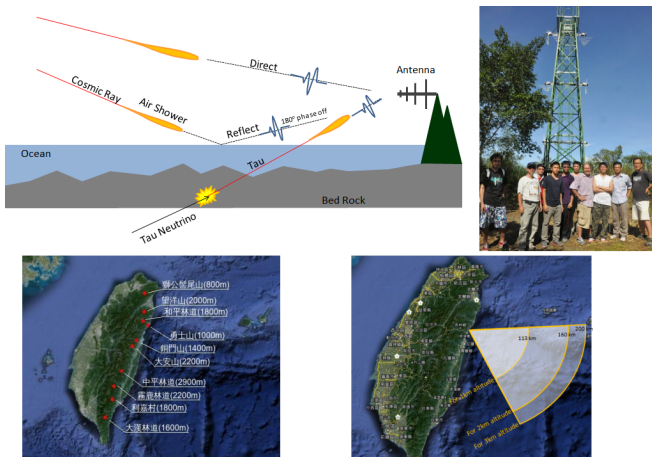
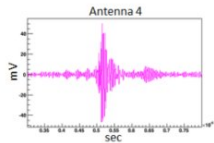
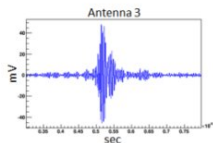
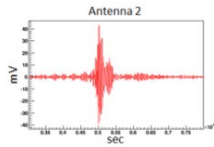
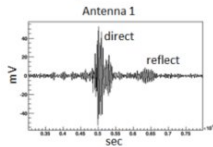
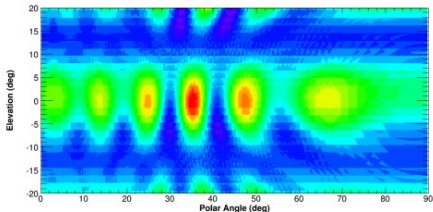
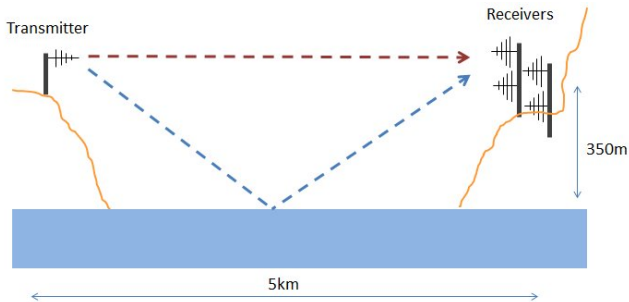


Figure : Large coverage (up to the horizon) and High Duty Cycle (~100%)

Reflection Test of TAROGE



TAROGÉ at 1200~2000m



TAROSE I



A prototype station at 1km height @ Heping

2 Antennas (6 V-pol + 6 H-pol)

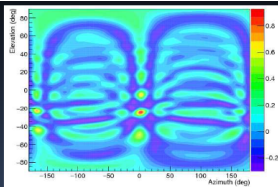
Deployed in July 2014

Successful year-round operation for noise survey

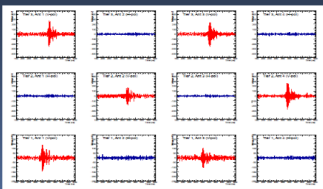
TAROE-1 Validation



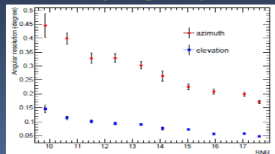
Calibration pulser system



Interferometry image of a pulser event



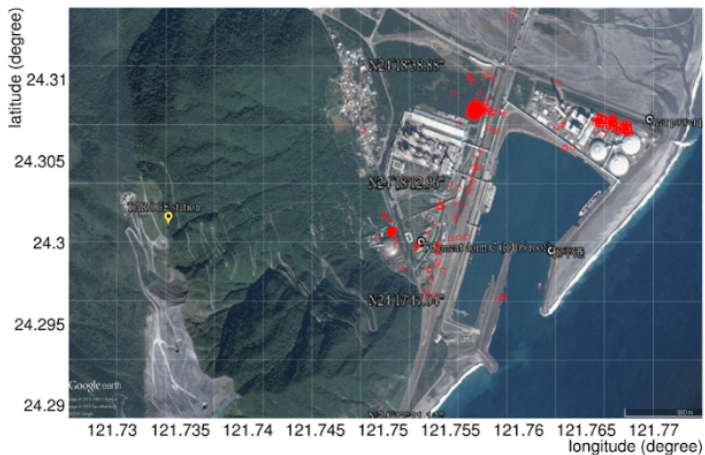
Recorded waveforms of a pulser event (V-pol)



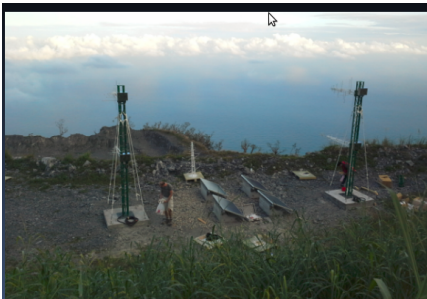
Angular resolution vs SNR

→ Excellent demonstration of detection concept and feasibility

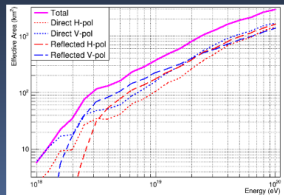
Noise Map



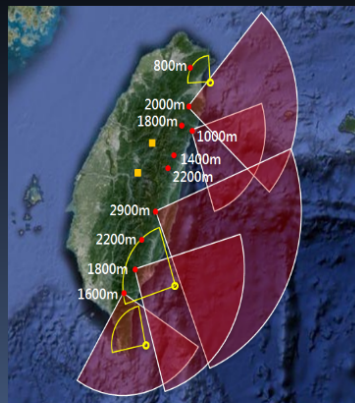
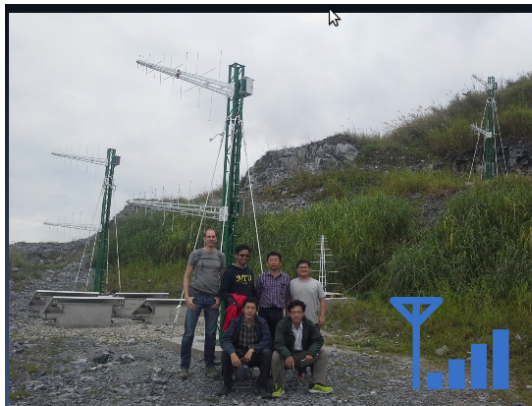
TAROGE-II



6 dual pol. LPDA antennas on 3 towers
 No town in FOV / CW insensitive trigger
 Longer baseline, time resolution improved
 → Better pointing resolution
 Off-grid power



TAROE 2 and Future



TAROE site candidates

Cross Section of Neutrino

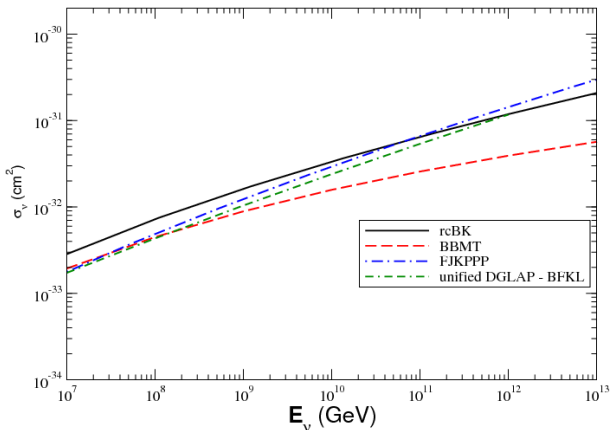


Figure : Neutrino cross section. 1 barn = 10^{-24} cm^2 . [Phys.Rev. D83 (2011) 014014]

Interaction Length of Neutrinos

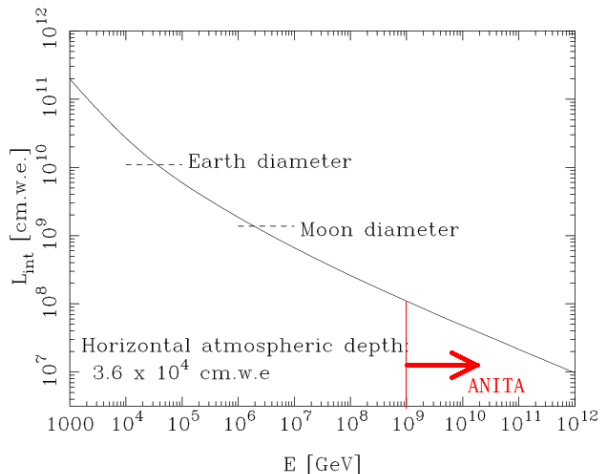


Figure : The neutrino interaction length (in centimeters water equivalent distance) [Astropart.Phys. 35 (2012) 383-395]

UHE Neutrino Interact with Earth

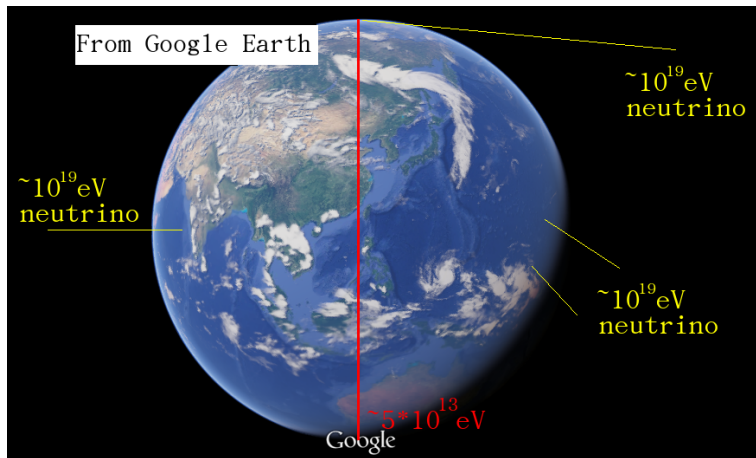


Figure : The interaction length of neutrino with $5 \cdot 10^{13}$ eV is close to diameter of Earth. The interaction length for 10^{19} eV neutrino is $6 \cdot 10^7$ g/cm².

Earth Skimming Events

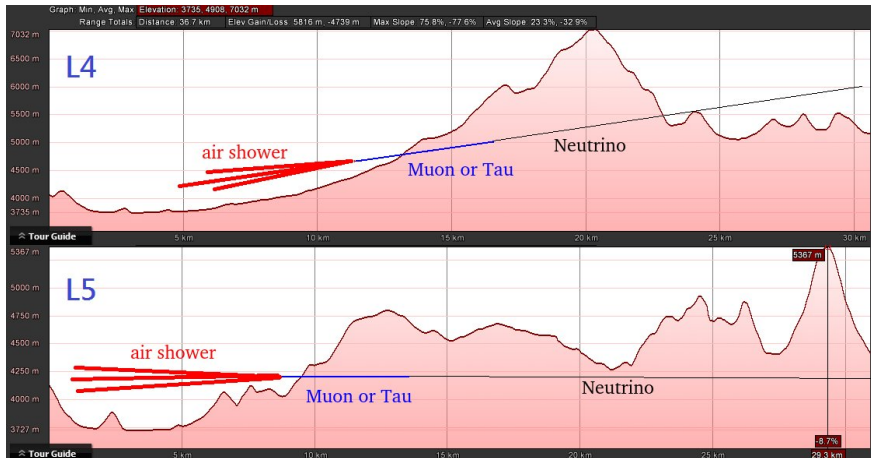


Figure : Neutrino intact with Earth and is converted to lepton. Lepton can generate Detector can detect the radiation that emit by induced air shower.

Noise Survey in Taiwan

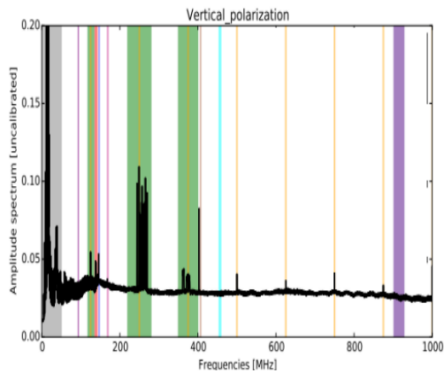
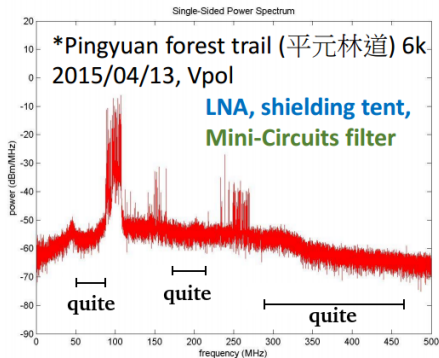


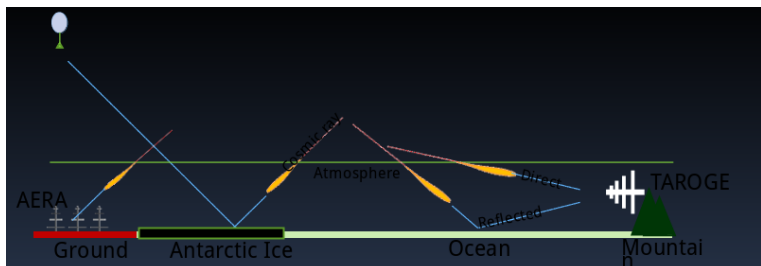
Figure : left: noise background in Taiwan mountain, right noise background in Antarctica.

Start the Trip from Now



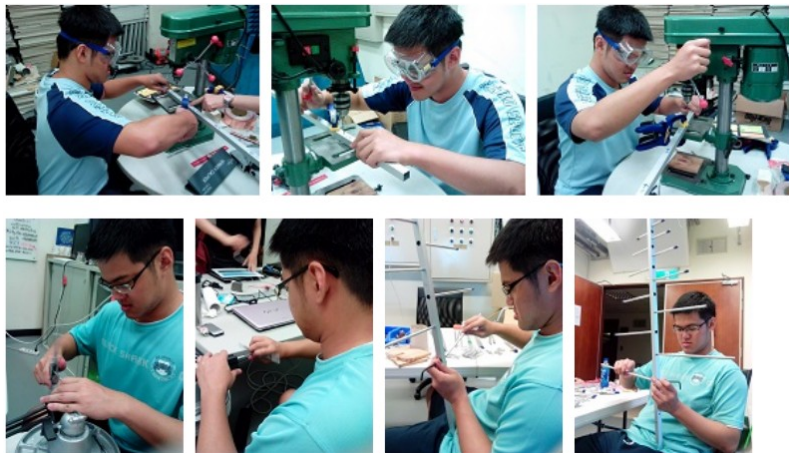
Figure : This survey is the most important trip of our project.

ANITA v.s. TAROGE



Parameter ^o	ANITA-I ^o	TAROGE (2km) ^o	Factor ^o
Detection Area ^o	$1.1 \times 10^6 \text{ km}^2$ ^o	$2.2 \times 10^4 \text{ km}^2$ ^o	0.02 ^o
Operation Time ^o	30 days / 3 years ^o	3 years ^o ☹️	36.5 ^o
Signal Direction ^o	Reflected ^o	Direct + Reflected ^o ☹️	1.5 ^o
Frequency ^o	200 MHz – 1GHz ^o	100-300 MHz ^o ☹️	^o
Integrated Signal Power ^o	70 pW ^o	130 pW ^o ☹️	
Geo-magnetic Field ^o	60 μT ^o	45 μT ^o	
Observation Height ^o	35 km ^o	2 km ^o	
Shower Height ^o	10 km ^o	10 km ^o	
Radio Path Length ^o	$45/\cos\theta \text{ km}$ ^o	$12/\cos\theta \text{ km}$ ^o ☹️	
Energy Threshold ^o	$5 \times 10^{18} \text{ eV}$ ^o	$1.4 \times 10^{18} \text{ eV}$ ^o ☹️	

Building Antenna



Summer intern student from FJU and NCTU making the antenna.

Testing Antenna

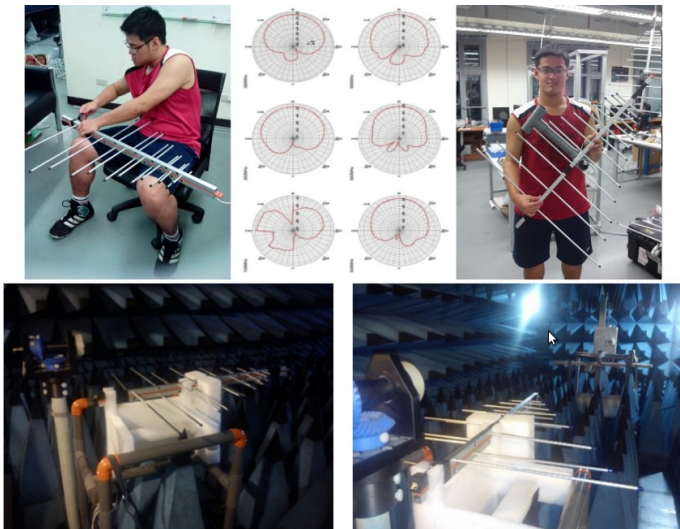
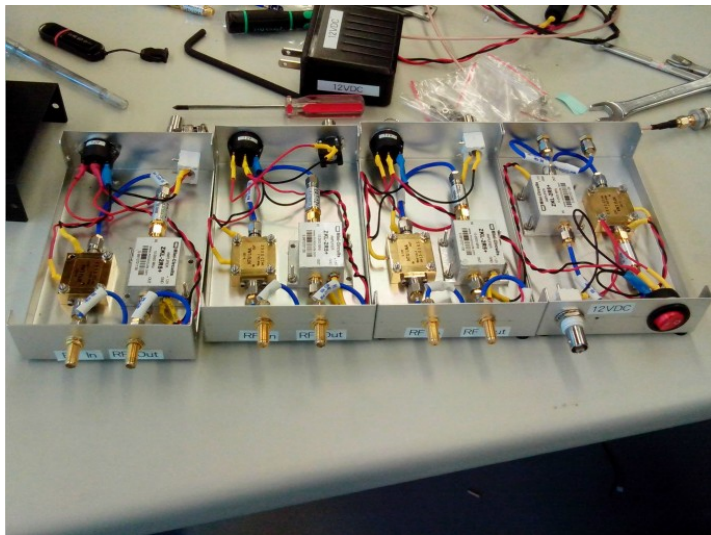


Figure : Summer intern students measure the antenna response.

LNAs of TAROGE



FoV of ANITA

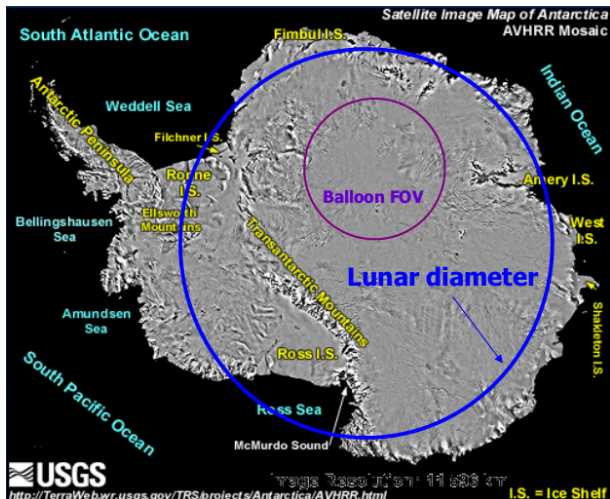
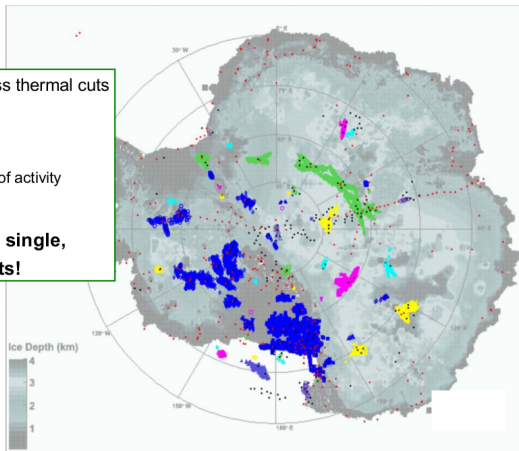


Figure : The radius of FoV is about 500km.

Man-Made EVENTS of ANITA

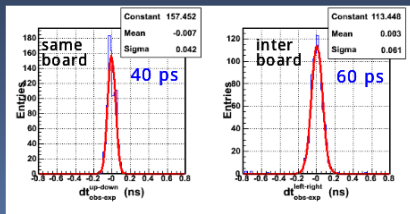
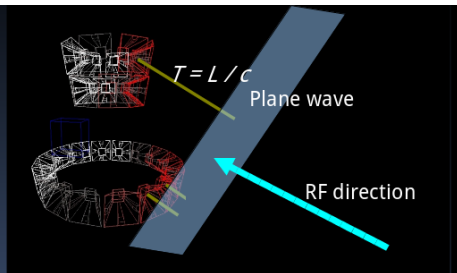
- 300k events pass thermal cuts
- Cluster with:
 - Other events
 - Known bases of activity
 - "Hot-Spots"
- **Neutrinos are single, isolated events!**



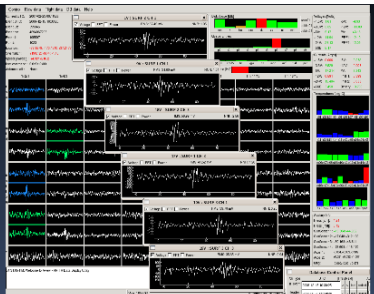
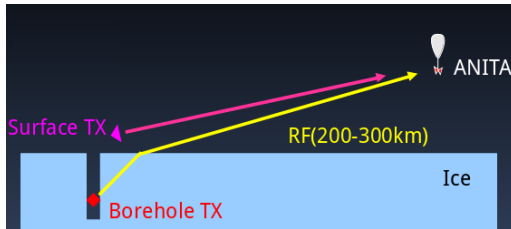
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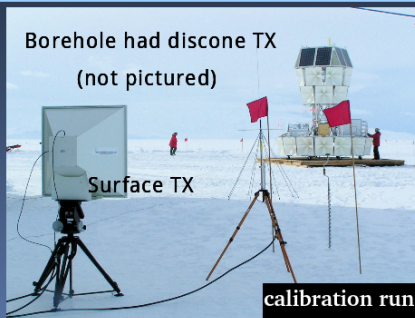
from jiwoo Nam



Ground Pulser System

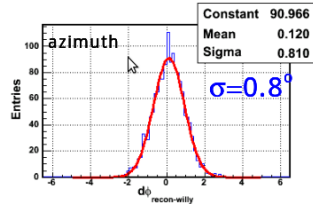
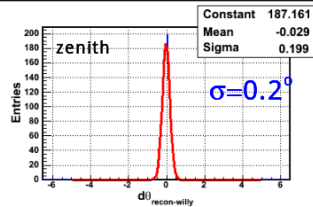
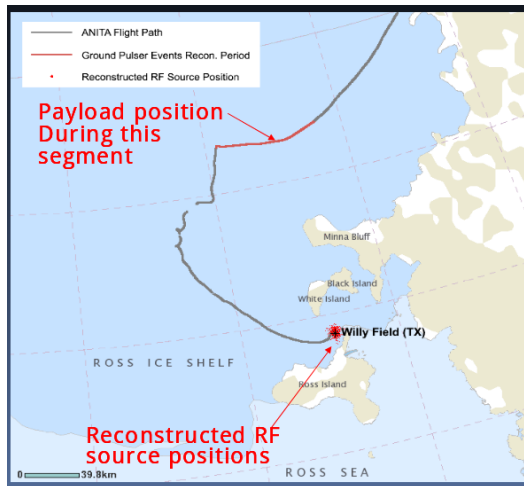


borehole pulse event

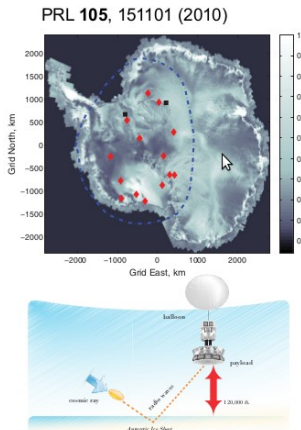


- Two Ground Pulser Systems @Williams Field and Taylor Dome
- System Verification
- Trigger Test
- Propagation and Surface
- Timing / Angular Resolution

Angular Resolution



Results of ANITA I & II (cosmic rays)



- A combination of $\mathbf{v \times B}$ and Fresnel coefficients result in air shower emission being horizontally polarised at the payload
- ANITA-I detected 16 isolated H-pol candidate UHECR events
- ANITA-II did not trigger on the H-pol channels
–Doh!!
- Still detected 5 UHECR candidate events

Results of ANITA I & II (Neutrino)

• ANITA-II Results

Isolated v-pol events	1
Expected background events	0.97 ± 0.42

- Combine with efficiency to extract world's best limit on UHE neutrino flux above 10^{19} eV

